LASER-BASED APPROACH FOR DETERMINING FLAKINESS INDEX OF AGGREGATES USED IN PAVEMENTS

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ABSTRACT

There are concerns about the standard methods/procedures for quantifying shape properties of rock aggregates used in road and airfield pavements. The CSIR has recently acquired a portable three-dimensional (3D) laser scanning device to address some of these concerns, i.e., to automate the determination of aggregate shape properties including form, angularity, texture, and flatness/flakiness. This paper presents a new approach to determine the flakiness index of rock aggregates used in pavements. The 3D laser device was used to directly measure the volume of aggregate samples used in five typical South African asphalt mixes. The results obtained from the laser device were used to compute flakiness index of the aggregate samples. The computed flakiness indices were in good agreement with the measurements from the standard methods, thus validating the correctness of the laser approach and the effectiveness of the volume method to compute flakiness index.

1 INTRODUCTION

The shape properties of rock aggregates used in asphalt mixes, Portland cement concrete, unbound base and subbase layers in roads and airfields have a significant influence on the engineering properties of the pavement structure (Ahlrich, 1996; Kandhal and Parker, 1998; Saeed et al., 2001; Meininger, 1998). The form (roundness/sphericity), angularity, and texture (roughness) of aggregate particles influence their mutual interactions and interactions with any binding/stabilising agents (e.g., bitumen, cement, and lime) and are related to durability, workability, shear resistance, tensile strength, stiffness, fatigue, permanent deformation, optimum binder content and, ultimately, performance of the pavement (Barksdale et al., 1992; Yeggoni et al., 1994).

The shape and volume parameters can be used to define the flakiness index of the aggregates. In South Africa, aggregate shape properties are quantified by flakiness index (*Technical Methods for Highways, TMH 1 Method B3* (TMH 1, 1986). The apertures of a slot gauge allow for considerable variation in the shape of different aggregates passing through. This may result in poor repeatability of flakiness index obtained from the same material. Similarly, two different aggregates having the same flakiness index may in reality differ significantly in terms of their shape and volume. A major problem is that the current standard test method involves a process, which is manual; it is often tedious and time consuming to be used on a daily bases for quality control. These shortcomings may be overcome by using advanced and automated measurement techniques.

A three-dimensional (3D) laser scanning device has recently been acquired by the CSIR to determine aggregate morphological properties, including texture/roughness, form (roundness, sphericity), angularity, flatness and elongation, flakiness, volume and surface area. The laser device has been evaluated for accuracy and repeatability (Anochie-Boateng et al, 2010). This paper focuses on the use of 3D laser-based volume approach to determine the flakiness index of rock aggregates commonly used in South African pavements. The flakiness index parameters obtained from the 3D laser scanning were compared with the results obtained from TMH 1 Method B3.

2 FLAKINESS INDEX OF AGGREGATES

The flakiness index parameter gives an indication of the flatness of a selection of aggregate particles. The flakiness index can be obtained from the shape/volume parameters (length, width and thickness) of the aggregates. The use of flaky aggregate particles in asphalt mixes is considered to be undesirable due to their tendency to break down during compaction and under traffic loading. Rock aggregates with high flakiness index often show high tendency to undergo crushing. In order to limit negative impacts of flaky aggregate particles, various guidelines specify the maximum flakiness index depending on the quality and the application for which the aggregates have been used.

In South Africa, the standard test method used for the determination of flakiness index of coarse aggregates is contained in TMH1 Method B3 (TMH 1 1986). In this method, a metal gauge with rectangular slots representing aggregate sieve sizes are used to obtain the masses of aggregate particles passing the slots. The flakiness index (in percent) is computed from the ratio of the mass of aggregate passing the gauge slots to total mass of aggregate retained on a specific sieve size (grading analysis). Mathematically, the flakiness index (FI) can be represented as follows:

$$FI = \left(\frac{M_p}{M_T} \right) \times 100 \tag{1}$$

where,

M_p = Total mass of aggregate passing slots;
M_T = Mass of the sample

Table 1 shows the Committee of Land Transport Officials (COLTO, 1998) and the Department of Transportation (DoT, *Draft TRH8: Design and use of hot-mix asphalt in pavements*) specifications for flakiness index in South Africa depending on the usage of the aggregate in the pavement structure.

Table 1 Flakiness index specification for aggregates

COLTO specs (max)				
Nominal size of aggregate (mm)	Surfacing aggregate		Rolling-in-chip (all grades)	Base (all grades)
	Grade 1	Grade 2		
19.0	25	30	20	35
13.2	25	30	20	35
9.5	30	35	-	-
6.7	30	35	-	-
DoT specs (max)				
Draft TRH8	Surfacing	Overlays	Base	Levelling
	30	35	20	20

3 LASER SCANNING OF AGGREGATE SAMPLES

3.1 3D laser scanning device

Figure 1 shows the 3D laser scanning device at the CSIR pavement materials testing laboratory. The device offers direct measurement of surface properties of regular and irregular shaped objects. It operates in both rotary and plane scanning modes to make it suitable for different types and sizes of rock aggregates. In the rotary mode, objects are scanned on a fully integrated rotating table using a laser beam, which travels vertically up the rotating object to generate a digital scan file. The plane scanning mode captures flat areas, hollow objects, oblique angles and fine details of objects with the laser beam, and can scan up to six surfaces at right angles. The laser device has been installed and calibrated to determine basic shape properties of conventional and non-conventional aggregates used in pavements.

An integral part of the 3D laser device is advanced data processing software, which allows users to merge scans for increased quality, change the shape around curved surfaces, sharpen edges, extend shapes, add thicknesses and perform Boolean operations on polygon surfaces. These features are essential for obtaining accurate morphological properties of the rock aggregates.

(a) 3D laser scanning device at CSIR BE (b) Sample aggregate on rotating table

Figure 1 Photo of laser scanning device at the CSIR pavement materials laboratory

3.2 Aggregates samples

Rock aggregates used in five asphalt mixes of South Africa road pavements were selected for this study. The mixes include the types used for asphalt surfacing and base courses of original, modified and bitumen rubber binders. Samples were taken from mix 1 (andesite), mix 2 (dolerite), mix 3 (dolomite), mix 4 (andesite) and mix 5 (quartzite). Sieve analysis tests were conducted on the blended aggregates using the standard South African sieve sizes described in TMH1 Method B4 (TMH1 1986).

Table 2 shows the grading results of blended aggregates for the five mixes. Following the grading analyses, the aggregate samples were riffled until the required number of particles needed for scanning was achieved.

Table 2 Sieve analysis (% passing) results and properties of mixes used in the study

Sieve Sizes (mm)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
26.5	100	100	100	100	100
19	93	93	100	100	100
13.2	82	80	100	100	96
9.5	71	73	95	97	74
6.7	58	67	80	75	43
4.75	51	50	62	59	27
2.36	36	34	40	42	17
1.18	25	23	28	30	11
0.600	18	17	21	21	7
0.300	14	12	16	14	5
0.150	8	9	10	9	3
0.075	5.4	5.7	5.5	5.8	2.6

Mix 1 = Bitumen treated base coarse mix with 40/50 penetration grade binder
Mix 2 = Coarse continuously graded mix with SBS modified binder
Mix 3 = Medium continuously graded mix with SBS modified binder
Mix 4 = Medium continuously graded mix with 60/70 penetration grade binder
Mix 5 = Semi-open graded mix with bitumen rubber binder

3.3 Scanning of aggregates

The 3D laser scanning device was used to scan the coarse aggregate particles (i.e particles large than 4.75 mm sieve) of the 5 asphalt mixes studied. The goal was scan a sample size of 30 from the population of aggregates retained on each sieve size to obtain a statistical representation of the aggregate samples except for the larger sieve size (i.e. 19 mm) where less than 30 particles were retained hence all of them were scanned.

Each aggregate particle was scanned to obtain 3D solid object with six plane faces. Planar mode scanning option of the laser device was firstly used to scan four faces followed by top and bottom to complete six faces. After completing the scanning, the software of the scanner was used to process a scan result in order to obtain a complete aggregate particle in six-face bounding box. Once the processing of the scan results were completed, the volume of the aggregates was obtained directly from the post-processing data. Figure 2 shows typical aggregate particles before and after scanning, and Figure 3 shows the scanned topographies of sample aggregates in 3D axonometric view in bounding boxes.

(a) Actual aggregates

(b) Scanned and processed aggregates

Figure 2 Actual aggregate particles and scanned particles of mix 2 retained on 19 mm sieve

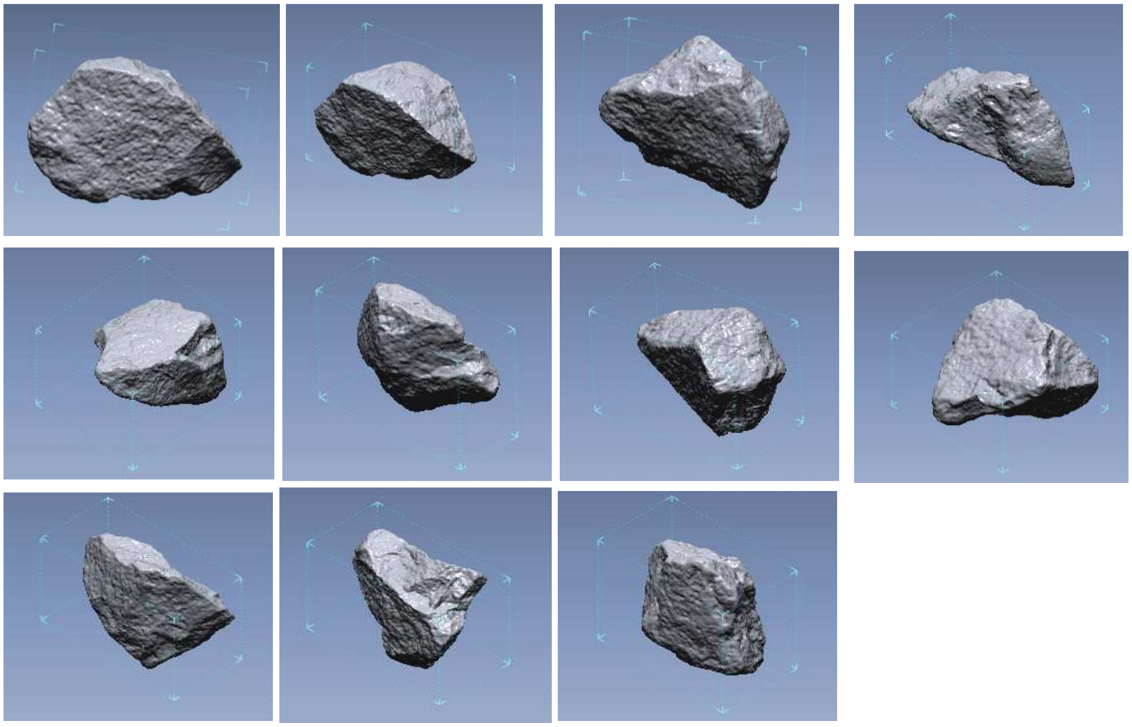

Figure 3 Scanned topographies of aggregates in bounding box - 3D axonometric view

Table 2 shows the total number of particles scanned for this study. Recall that a sample size of 30 was targeted for scanning. However due to the fact that limited number of particles are usually retained on large sieve sizes during grading analysis, less than 30 particles were scanned in some sieve sizes. Mixes 1 and 2 had 17 and 11 particles (i.e., < 30 particles) retained on the 19-mm sieve size, respectively, implying that all the aggregate particles retained on this sieve were scanned. Also, mix 5 had 26 particles retained on 13.2-mm sieve, which were all scanned. On the average, a total of 30 minutes was used for scanning and processing of individual aggregate particle.

Table 2 Aggregate particles scanned for each mix

Sieve Sizes (mm)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Total
26.5	-	-	-	-	-	-
19.0	17	11	-	-	-	28
13.2	30	30	-	-	26	86
9.5	30	30	30	30	30	150
6.7	30	30	30	30	30	150
4.75	30	30	30	30	30	150
Total	137	131	90	90	116	564

4 LASER-BASED DETERMINATION OF VOLUME AND FLAKINESS INDEX

4.1 Volume of aggregates

The volumetric parameters of individual aggregate particle were determined directly from the 3D laser scanning device for the computation of flakiness index of the aggregates samples. For comparison purposes, the standard TMH 1 Method B3 was also used for determining flakiness index of all aggregate particles scanned.

Aggregate particles originating from the same parent rock are usually assumed to have the same specific gravity hence the ratio by mass is equivalent to the ratio by volume. With this in mind, the mass of all aggregates scanned were derived from the volume data directly obtained from the 3D laser device.

To verify the capability of the laser scanning approach for accurate measurement of volume of aggregate, the total volume of scanned aggregates retained on a specific sieve sizes were used to compute the mass. The density values used for the five mixtures studied were mix 1 (2815 kg/m^3), mix 2 (2930 kg/m^3), mix 3 (2873 kg/m^3), mix 4 (2809 kg/m^3) and mix 5 (2738 kg/m^3). It is observed that the use of bulk density instead of specific gravity of individual aggregate particle to determine the mass of the aggregate can be a source of error in the computed mass of the aggregates. Equation 2 was used to derive the mass of the aggregate samples scanned.

$$M = D \times V \quad (2)$$

where, M = mass of aggregate; D = density of aggregate; V = volume of aggregate

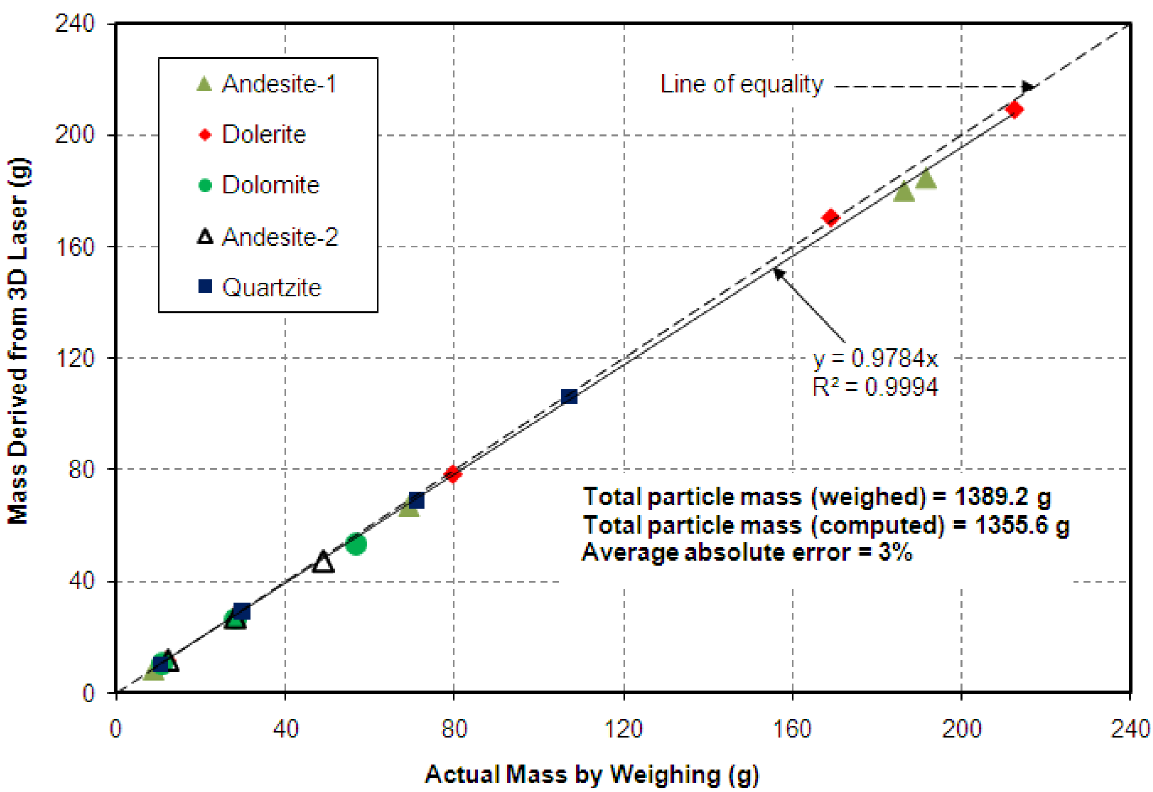

Figure 4 Comparison of total masses for the aggregate samples of the 5 mixes

Figure 4 presents a plot of the actual mass of the aggregates (564 in total from five parent rocks) obtained by weighing, and the derived masses for all the aggregates scanned. It can be seen that the mass of the aggregates estimated from the CSIR 3D laser device agree quite well with the physically measured (weighed) values. An excellent correlation (R^2 = 0.9994) exists between the computed and the actual mass although there is an insignificant error, which may be due to the use bulk densities instead of specific gravities of the individual aggregates in Equation 2.

4.2 Flakiness index of aggregates

Both TMH 1 Method B3 and the 3D laser scanning approach were used to determine the flakiness index of the aggregate samples. It should be noted that flakiness index obtained from the standard THM 1 method B3 is based on mass whereas the approach introduced in this paper using the 3D laser scanning technique is based on the volume of the scanned aggregates. The following steps were followed to compute the flakiness index using the 3D laser scanning technique:

- Dimensions (length, width and thickness) of the individual aggregate particle were obtained directly from the 3D bounding box.
- Flaky particles were determined by comparing the dimensions of the 3D bounding box of individual aggregate particles with that of the standard gauge slots.
- Total volume of scanned aggregates and volume of flaky aggregate particles were obtained from the 3D laser results.
- Finally, flakiness index was calculated by dividing the total volume of flaky particles by the total volume of the sample.

The flakiness index based on 3D laser concept of volume can mathematically be represented as follows:

$$FI_v = \left(\frac{V_p}{V_T}\right) \times 100 \qquad (3)$$

where,

FI_v = Flakiness index based on volume;
V_p = Total volume of flaky aggregates scanned;
V_T = Total volume of the aggregate sample

Table 3 shows the flakiness index computed for all the aggregate samples using the standard TMH 1 Method B3 and the 3D laser scanning technique. Figure 5 compares the flakiness indices from these two test methods. Recall that the volume approach used by the 3D laser device predicted very well the mass of the aggregates scanned. Note that the data points for mixes 1 (andesite) and 2 (dolomite) plots are far from the line of equality when compared to the data points of (i.e., mixes 3 and 4). It is worth to mention that mixes 3 and 4 are medium continuously graded (i.e., relatively smaller size aggregates) when compared with mixes 1, 2 and 5 (coarse graded). Thus, in comparison with the medium graded mixes, the flakiness index values obtained for the three coarse graded mixes have high error values.

The tendency of the technicians, who are performing flakiness index test to force a coarse aggregate particle to pass through the metal gauge slots by pushing it harder, could introduce a significant error in the flakiness index since coarse aggregate particle weighs by far more than medium or small size aggregate particle. That is, human errors could significantly affect the determination of flakiness index of aggregates particles using TMH1 Method B3. One the other hand, in the 3D laser scanning approach (automated), aggregate particles are conveniently placed in a 3D bounding box by the laser scanning software for the computation of flaky particles. This automated procedure would mitigate the human errors associated with the manual method, i.e., TMH1 Method B3.

Generally, the observed trends in the flakiness index results (Table 3) support the call by pavement engineers and practitioners on the use of automated systems to quantify the shape and surface properties of rock aggregates used in pavements.

Table 3: Flakiness index (in percent) results

Asphalt mix	TMH 1 Method B3	3D Laser technique	Error
1	29.6	24.8	4.8
2	17.1	13.2	3.9
3	15.5	15.4	0.1
4	4.7	5.3	-0.6
5	23.8	24.8	-1.0

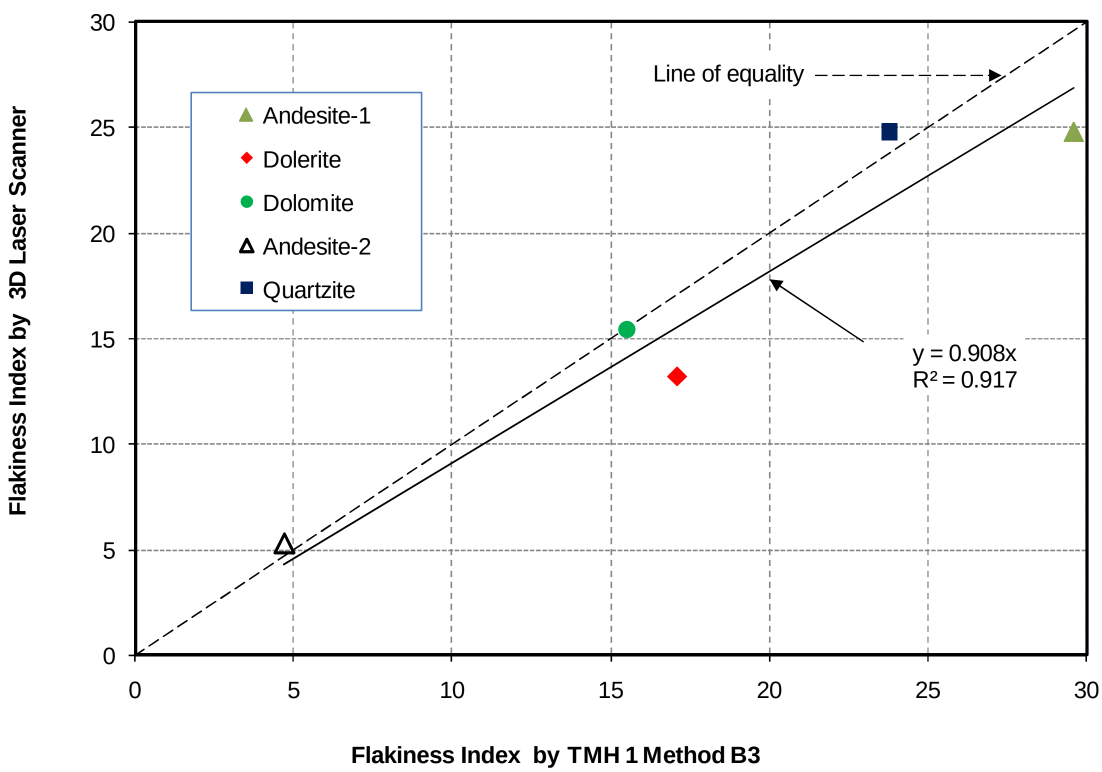

Figure 5 Comparison of flakiness index determined from TMH 1 and 3D laser technique

5 CONCLUSIONS

The fundamental measurements of aggregate shape characteristics are essential for good quality control of aggregates in the pavement and, ultimately, for understanding their influence on performance of the pavement layers. Flakiness index is a measure of the flatness of an aggregate particle. The current test method for determining flakiness index of aggregates in South Africa has some limitations; most importantly, it is laborious and subjective in nature, which may lead to poor repeatability.

This paper introduced a new approach for the determination of flakiness index of aggregates. The approach is based on the use 3D laser scanning technique to directly obtain the volume of an aggregate particle, and use the volume parameters to compute flakiness index. Overall, aggregate samples used in five common asphalt mixes in South Africa were studied. The results show that the mass of aggregates derived from the volume obtained from the 3D laser scanner were in a very good agreement with those obtained physically by weighing. In addition, there was an overall good agreement between the flakiness indices of aggregates used in the medium continuously graded mixes. However, the flakiness indices of the aggregates used in the coarser mixes did not compare well for the two methods.

Based on the results presented in this paper, the following conclusion can be made:

- There is a need for fast, accurate and automated method/procedures to determine flakiness index of aggregates used in pavements.
- There is a need to mitigate human errors associated with aggregate shape properties quantification and analyses.
- The CSIR 3D laser scanning device shows potential for obtaining accurate measurement of shape and surface properties of rock aggregates used in pavements.

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